A STORM WATER MANAGEMENT MODEL TO PREDICT RUNOFF AND STREAMFLOW IN THE PENNICHUCK BROOK WATERSHED

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Engineering

by

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January 2007

ABSTRACT

Due to continuing property development in the area much of the Pennichuck Brook Watershed has transformed from wooded areas and farmland into residential and commercial districts with a large amount of impervious area. The result has been increased runoff and pollutant loadings to the chain pond water supply system operated by Pennichuck Water Works. The new EPA Storm Water Management Model (SWMM) Version 5.0.006a was used to assess the condition of this watershed. Utilizing the aquifer sub-model the SWMM model was calibrated to the Pennichuck Brook Watershed. Due to the large volume of precipitation percolating into the ground, the aquifer component was necessary to determine groundwater flow to surface waters. Stream gaging stations were set up and streamflows were measured to develop stage discharge curves for each of the nine gaging stations throughout the watershed. Water level data loggers were installed at these sites where stream levels were recorded from September 29, 2005 through May 4, 2006. These levels were converted into continuous streamflow records that were subsequently used in model calibration and validation procedures. Problems encountered in this project included heterogeneities in the aquifers and heterogeneities in the precipitation neither of which were modeled due to lack of sufficient data. Additionally, there were several gaps in the streamflow records as a result of wildlife interference and datalogger batteries failing. The calibrated SWMM model provides a reasonably accurate model for predicting runoff and streamflow in this watershed. The coefficients of determination

were 0.50 and 0.86 for the model calibration and validation, respectively. On average the model predicted lower streamflow rates and volumes than were observed in the field most likely due to inter-watershed groundwater flow.

BIOGRAPHICAL SKETCH

Jacob (Jack) Troidl grew up in Middleburgh, a small rural community in upstate New York with his parents, Robert and Marjorie, and older brother, Robert. At Middleburgh Central School, Jack was active in athletics, participating on the basketball and baseball teams. He was also very involved in outdoor activities including dirt biking, skiing, and snowmobiling. After graduating from high school in 1998, Jack was accepted at Cornell University where he earned his Bachelor of Science degree in Biological and Environmental Engineering in January 2002. He immediately began his Master of Engineering program at Cornell and later continued working on his degree while working full-time as an Environmental Engineer in the Greater Boston area. Jack moved to this area to be near his girlfriend (now fiancée), Judy Chan. Jack is currently pursuing his Professional Engineering license.

To my parents and my fiancée

ACKNOWLEDGMENTS

I would like to thank my advisor, Professor Tammo Steenhuis, of the Department of Biological and Environmental Engineering for his continued efforts, guidance, and support in helping me pursue this degree. I would also like to thank my financee, Judith Chan, as well as my parents, Robert and Marjorie Troidl for their never-ending support and encouragement. They truly motivated me to complete this endeavor. Finally, I would like to thank Pennichuck Water Works and the Nashua Regional Planning Commission for allowing me to use their data for this project.

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CHAPTER 1

INTRODUCTION

Background

The Pennichuck Brook Watershed encompasses 28 square miles within Southern New Hampshire. This watershed is a water supply system composed of four chain ponds along Pennichuck Brook with a withdrawal point at Harris Pond (Figure 1-1). Pennichuck Water Works (Pennichuck) supplies the City of Nashua and several other surrounding communities with clean, filtered water from this chain pond water supply system.

Water quality in this system has been threatened from increased stormwater runoff, a result of both commercial and residential development in the watershed. Impervious area increases as more area in the watershed is developed, preventing recharge to groundwater. Recharge to groundwater provides a more constant supply to streamflow of higher quality water during non-runoff periods. In addition, impervious runoff contains higher pollutant concentrations than runoff from natural areas. Surface water of poorer quality is laden with sediment from both erosion and winter sanding applications which is ultimately deposited into streams, wetlands, and the four chain ponds. Each year, as the sediment fills up the reservoirs, less capacity is available for water supply storage, and conditions become less favorable for pollutant settling and deposition.

If development continues unregulated and the appropriate stormwater controls are not implemented, water quality will degrade to a point where additional water treatment methods are needed in order to meet regulatory water quality requirements

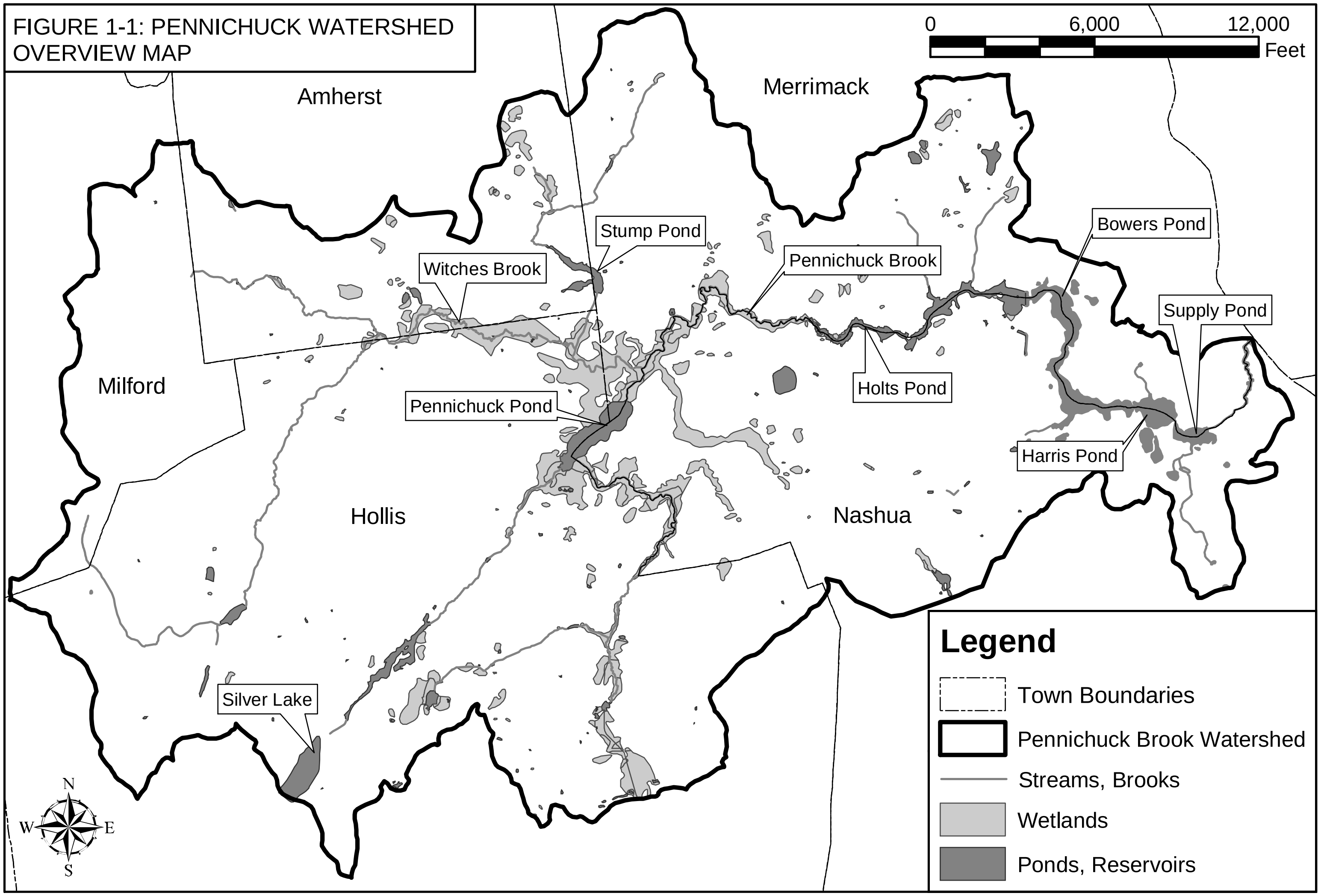


FIGURE 1-1: PENNICHUCK WATERSHED OVERVIEW MAP

for drinking water. This could lead to a very costly and time-consuming endeavor of cleaning up the watershed after the fact. The alternative is for Pennichuck Water Works to take a proactive position and protect their water supply system from the possible degradation resulting from development.

Scope of Work

Modeling is needed to assess future conditions of the watershed. The Storm Water Management Model (SWMM) was chosen because of its versatility and proven abilities from other modeling applications (Rossman, 2005). This project consists of the initial watershed assessment which is to determine runoff, streamflow, and pond levels throughout the watershed. The SWMM model is used to model runoff from the entire watershed as well as route these flows through the various streams and ponds. Several monitoring and sampling locations are being used by Pennichuck and the Nashua Regional Planning Commission (NRPC). The watershed is divided into smaller sub-watersheds according to these locations. The model is calibrated using flow monitoring data obtained as part of this project. Determining the amount of runoff and consequently the water entering the reservoirs provides a basis for determining the water quality in the reservoir system. Future work with the model involves incorporating a water quality component. This will include modeling water quality in the runoff, streamflow, and ultimately in the reservoirs. A simple lake model will be required for the reservoir component. Areas with high pollutant loadings will then be isolated and identified as hydrologically sensitive areas. This will aid in selecting the appropriate stormwater best management practices (BMPs) and identifying the locations where they should be implemented in order to improve water quality to desired levels.

Physical Description

The Pennichuck Brook Watershed is comprised of approximately 18,000 acres of a variety of land uses from rural farm land to densely populated sections in Nashua (Figure 1-2) (Nashua Regional Planning Commission, 2005). The watershed lies within five communities, namely Amherst, Hollis, Merrimack, Milford and Nashua (Figure 1-1). This area experiences the typical New England climate. The average annual precipitation is 45.3 inches (Yahoo Real Estate, 2006). The average winter's high and low are 33 and 11 degrees Fahrenheit, respectively (Yahoo Real Estate, 2006). The average summer's high and low are 82 and 60 degrees, respectively (Yahoo Real Estate, 2006). The soils throughout the watershed typically have rapid infiltration rates, which cause much of the precipitation to feed into the streams as baseflow.

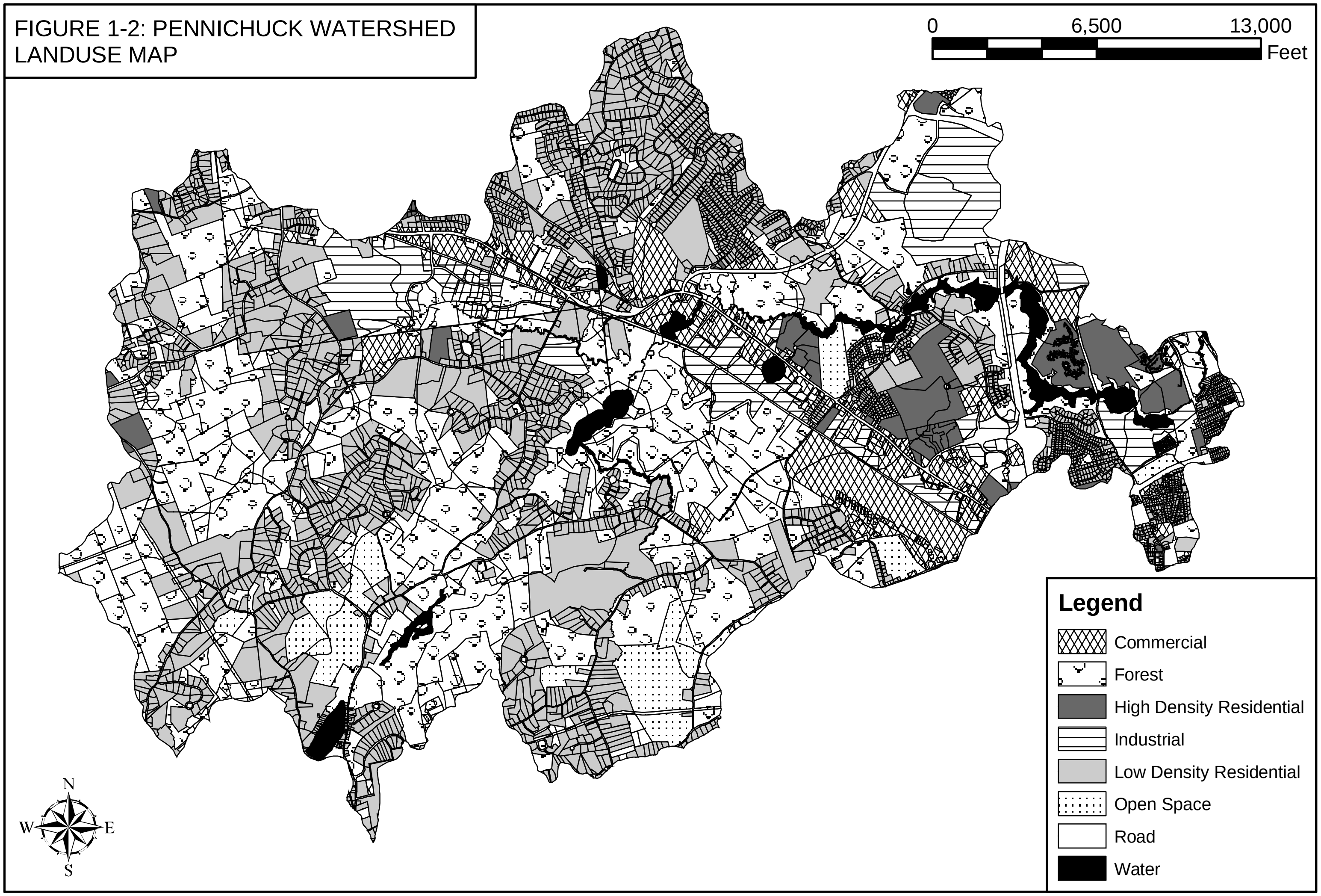


FIGURE 1-2: PENNICHUCK WATERSHED LANDUSE MAP

CHAPTER 2

MODEL DEVELOPMENT

Storm Water Management Model

The model used for this application is the EPA Storm Water Management Model (SWMM) Version 5.0.006a (Rossman, 2005). The original SWMM model was developed in 1971. This new, Windows-based, version provides easy-to-use input screens and graphic results. It was chosen because the model is versatile and as more data becomes available, the model can be modified to incorporate future BMPs and simulate water quality. This model also provides modules for snowmelt calculations, and hydraulic modeling capabilities for drainage system modeling. These features are not being used in this paper, but will most likely be used for future model revisions as more data becomes available and a higher resolution is desired.

Routing Method and Time Steps

Three routing methods are available in the model, namely steady flow routing, kinematic wave routing, and dynamic wave routing. The steady flow routing method assumes flow is uniform and steady within each time step and therefore does not provide for channel storage, travel time, etc. Kinematic wave routing uses a simplified momentum equation in each conduit. Each conduit can provide flow up to its maximum flow as calculated by Manning's Equation. Excess flows can be stored in the upstream node and then routed when capacity is available. Dynamic wave routing, theoretically the most accurate routing method, uses the one-dimensional Saint Venant flow equations (Rossman, 2005).

Dynamic routing provides a very accurate representation but requires a very small time step and therefore causes model run time to increase significantly. It is not needed here because the scope of this project focuses on stormwater and overall runoff rates instead of flow routing and flood modeling which would require detailed flow channel characteristics. Kinematic wave routing was chosen because it provides an efficient means of flow routing.

The model allows the time steps to vary depending on the hydrological conditions. Dry periods use a time step of ten minutes and wet periods use a time step of five minutes. The routing time step is set at 300 seconds (five minutes) to provide a reasonably accurate streamflow routing method. All model outputs are reported in one-hour intervals for model calibration and validation.

Time Period

The model was run from April 1, 2005 until the most recent available data on May 8, 2006. Streamflow data was recorded during various periods between September 29, 2005 and May 4, 2006. This data is used for model calibration and validation.

Infiltration Sub-Model

EPA SWMM 5.0 provides three options for calculating infiltration, namely Horton's Equation, Green-Ampt Method, and the Curve Number Method (Rossman, 2005). Horton's Equation was used because of available soil data. Infiltration rates are contained in the New Hampshire Soil Attribute Data Dictionary reference table (Natural Resources Conservation Service, 2001) for the soils GIS data layer and typical values for the remaining parameters were provided in the SWMM model.

Although the Curve Number method was considered, it was determined that it is not appropriate for soils with such high infiltration rates.

Runoff and Baseflow Sub-Model

The sub-model calculates surface runoff as well as subsurface aquifer discharge to the streams (baseflow). Figure 2-1 shows the overall model of the runoff components. The surface model consists of a reservoir with the depth equal to the depression storage over the respective watershed area. Depression storage is the amount of water that will puddle on the ground surface resulting from an irregular surface. This component consists of two parts in each subwatershed, impervious and pervious areas. The reservoir has an input of rainfall and three outflow components: evapotranspiration, infiltration and runoff. Once the capacity of the reservoir, evapotranspiration, and infiltration have been exceeded, surface runoff begins which immediately feeds the downgradient stream. The infiltration component feeds the baseflow model which simulates surface-groundwater interactions (Rossman, 2005).

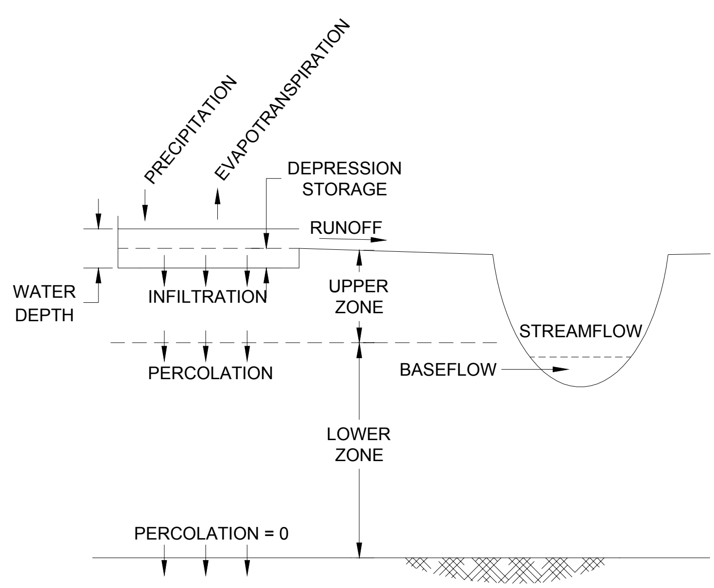


FIGURE 2-1: SURFACE RUNOFF / BASEFLOW MODEL

The baseflow model has two parts: the upper unsaturated zone and the lower saturated zone. Initial model runs did not incorporate the aquifer and baseflow components of the model; however, these were quickly added based on the initial results. The upper unsaturated zone represents the root zone and the lower saturated zone represents the aquifer which is capable of providing baseflow to the streams. This model includes evapotranspiration which enables the use of the unused evaporation from the surface model. The elevation of the lower zone is related to the elevation of the stream bottom. As the water table exceeds the bottom elevation of the stream channel, flow from the aquifer is allowed to enter the stream channel. In order to simplify the model, reverse flow into the aquifer was not simulated. The simplified equation below modified from the version in the SWMM Manual (Rossman, 2005) was used to calculate baseflow:

$$GwFlow = A1\,(D1 - BC)^{B1}$$

GwFlow = Groundwater discharge into the stream (cfs/acre)
A1 = Groundwater flow coefficient
D1 = Elevation of water table in aquifer (ft)
BC = Elevation of stream channel invert (ft)
B1 = Groundwater flow exponent

CHAPTER 3

INPUT DATA

Comprehensive Environmental Incorporated (CEI) is an environmental engineering and consulting firm that Pennichuck had previously hired to perform various watershed projects. Initially, CEI had partitioned the watershed into ten subwatersheds (Comprehensive Environmental Incorporated, 2005). Many of the sampling locations were created after this delineation and did not coincide directly with the subwatershed delineations. These locations are typically located at culverts along roadways which provide easy and safe access to the streams. To facilitate model calibration, the subwatersheds were further reduced to drainage areas of these sampling locations. Subwatersheds were delineated based on topography, hydrologic boundaries, and these sampling sites.

GIS Data

The majority of data for the model was available as spatial data in a Geographic Information System (GIS). A GIS includes georeferenced information which can then be read, modified or analyzed. GIS data was available from NRPC, CEI, and the State of New Hampshire GIS also known as Geographically Referenced Analysis and Information Transfer (GRANIT). The layers available for use are described in Table 3-1 below. ArcView 8.3 was used for all GIS work except where ArcView 3.2a was required to use the SWMM Tools extension.

Table 3-1: Existing GIS Data			
GIS Layer	Model Use	Type	Source
Parcels	Mapping	Vector-Polygon	(NRPC, 2005)
Landuse	Landuse, Imperviousness	Vector-Polygon	(NRPC, 2005)
Landcover	Evapotranspiration Cover Coefficients	Vector-Polygon	(GRANIT, 2001)
Soils	Infiltration Rates, Soils Parameters	Vector-Polygon	(GRANIT, 2006b)
Subwatersheds	Subcatchments	Vector-Polygon	(CEI, 2005)
Hydrography	Streams, Ponds, Reservoirs	Vector-Polygon/Polyline	(GRANIT, 2006a)
Orthophotos	Mapping	Raster-Image	(GRANIT, 2003)
USGS Topographic Maps	Elevation Data	Raster-Image	(GRANIT, 2004)

Precipitation Data

Precipitation data was obtained from the National Climatic Data Center (NCDC) (National Climatic Data Center, 2006). This consisted of hourly data for the Concord Municipal Station 271683 from April 1, 2005, until September 1, 2006. This is the closest station with a continuous period of record for precipitation data. The weather station located in Nashua did not have any significant periods of continuous precipitation data available. In addition to this data, data from several personal weather stations in the area was examined. Weather data from KNHNASHU10 in South Nashua was also used in the model (JL, 2006). Precipitation from this station when compared to other stations available at this site showed a high variability in rainfall throughout the watershed. This station seemed to best fit the runoff events of the watershed and was combined with the Concord precipitation data in an hourly format to form the precipitation inputs for the model. A composite precipitation file was created from these two sources from April 2005 to May 2006 (Appendix A).

Evapotranspiration Data

Potential evapotranspiration within each subwatershed was modeled using the temperature-based Hamon Equation (Hamon, 1961). This method was chosen because of its simplicity and availability of inputs for the equation. Hourly temperatures were used to estimate the Potential Evapotranspiration (PET). Monthly average hours of daylight were used in the equation (Table 3-2). The watershed is located at approximately 42 degrees north latitude.

Table 3-2: Mean Daylight Hours for 42° N Latitude (Mills et al, 1985)

Month	Daylight (hrs)
January	9.3
February	10.4
March	11.7
April	13.1
May	14.3
June	15.0
July	14.6
August	13.6
September	12.3
October	10.9
November	9.7
December	9.0

Shown below are the equations used for this calculation taken from (Hamon, 1961) and (Bosen, 1960) respectively:

$$PE_t = \frac{0.021\, D_t^2\, e_{st}}{T_t + 273} \qquad \text{where} \quad T_t \geq 0$$

$$E_{st} = 33.8639\ [\ (0.00738\ T_t + 0.8072)^8 - 0.000019\ (1.8\ T_t + 48) + 0.001316]$$

PE_t = Potential Evapotranspiration (in)
D_t = total number of hours of daylight on day (hrs)
E_{st} = Saturated water vapor pressure (mb) at time t
T_t = Mean Air Temperature at time t (°C)

In 2001, New Hampshire completed a state-wide Land Cover Assessment (GRANIT, 2001). This layer consists of 100 foot grid cells across the state. Evapotranspiration was modeled using a cover coefficient equal to 1.0 (Haith, Mandel, and Wu, 1992). Therefore, the potential evapotranspiration is equal to the actual evapotranspiration provided that there is sufficient water in depression storage or the upper zone of the aquifer. This is representative of grass, meadow and softwood forests in both the dormant and growing seasons. This type of surface is consistent with the majority of the pervious surfaces throughout the watershed. Evapotranspiration from the upper zone is equal to the lessor of the maximum evapotranspiration input minus surface water evaporation or the fraction of evapotranspiration assigned to the upper zone times the maximum total evapotranspiration. Evapotranspiration is equal to zero if the moisture content is less than the wilting point and when infiltration occurs (Huber and Dickinson, 1988). A daily summary of the hourly evapotranspiration is included in Appendix B and a sample of the input data is shown below (Table 3-3).

Table 3-3: Sample of Potential Evapotranspiration Inputs

Date	Hour	Month	Temperature (°F)	Temperature (°C)	Daylight (hours)	Potential ET (in/day)
10/31/05	20:00	10.00	55.40	13.00	10.90	0.059
10/31/05	21:00	10.00	52.70	11.50	10.90	0.054
10/31/05	22:00	10.00	52.90	11.61	10.90	0.055
10/31/05	23:00	10.00	51.00	10.56	10.90	0.051
11/01/05	0:00	11.00	48.90	9.39	9.70	0.038
11/01/05	1:00	11.00	48.00	8.89	9.70	0.036
11/01/05	2:00	11.00	47.70	8.72	9.70	0.036
11/01/05	3:00	11.00	47.10	8.39	9.70	0.035
11/01/05	4:00	11.00	44.60	7.00	9.70	0.032
11/01/05	5:00	11.00	42.90	6.06	9.70	0.030

Subwatershed Properties

The Pennichuck Brook watershed is divided into 24 subwatersheds (defined as subcatchments in SWMM) (Figure 3-1). Initial subwatershed properties are displayed in Table 3-4. Descriptions of these parameters are below.

Area, Width, & Slope

Subwatershed areas were calculated in ArcView based on the subwatershed delineations. Subcatchment width defines the width of the overland sheet flow which drains to the main drainage channel. It is suggested to use a width equal to 1.7 times the length of the main stream channel (Huber and Dickinson, 1988). Widths were initially calculated using an ArcView 3.2a avenue script "SWMM Tools" (Heineman, 2002). This utility calculates the width as 1.7 times the longest extent of the subwatershed polygon. The length of the subwatershed's extent may not be equal to the stream channel, but this provides a reasonable estimate of its length. This parameter is a calibration parameter used to match the modeled runoff to measured hydrographs. The slope of each subcatchment was calculated by reading the highest point elevation and the lowest point elevation from USGS topographical maps (GRANIT, 2004) along the main stream channel (Figure 3-2). The distance along this flow path was then used to determine the average slope.

Land Use Data

Two land use layers are available for the Pennichuck Watershed. These are the NRPC parcel-based land use layer and the 2001 GRANIT land cover assessment. The NRPC layer was developed from assessor parcels and land use for the parcel whereas the land cover assessment was based on aerial mapping using a grid format. The land

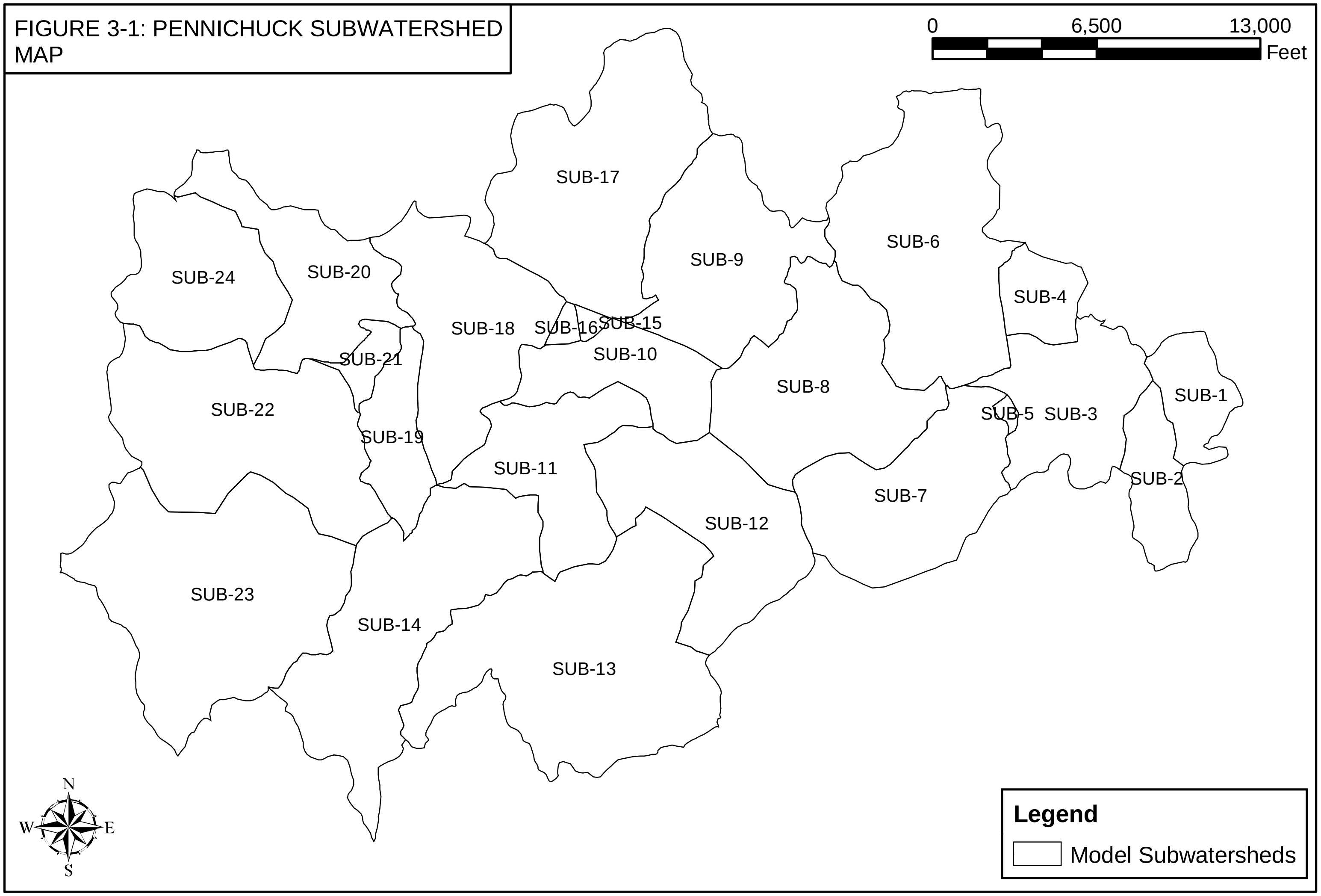
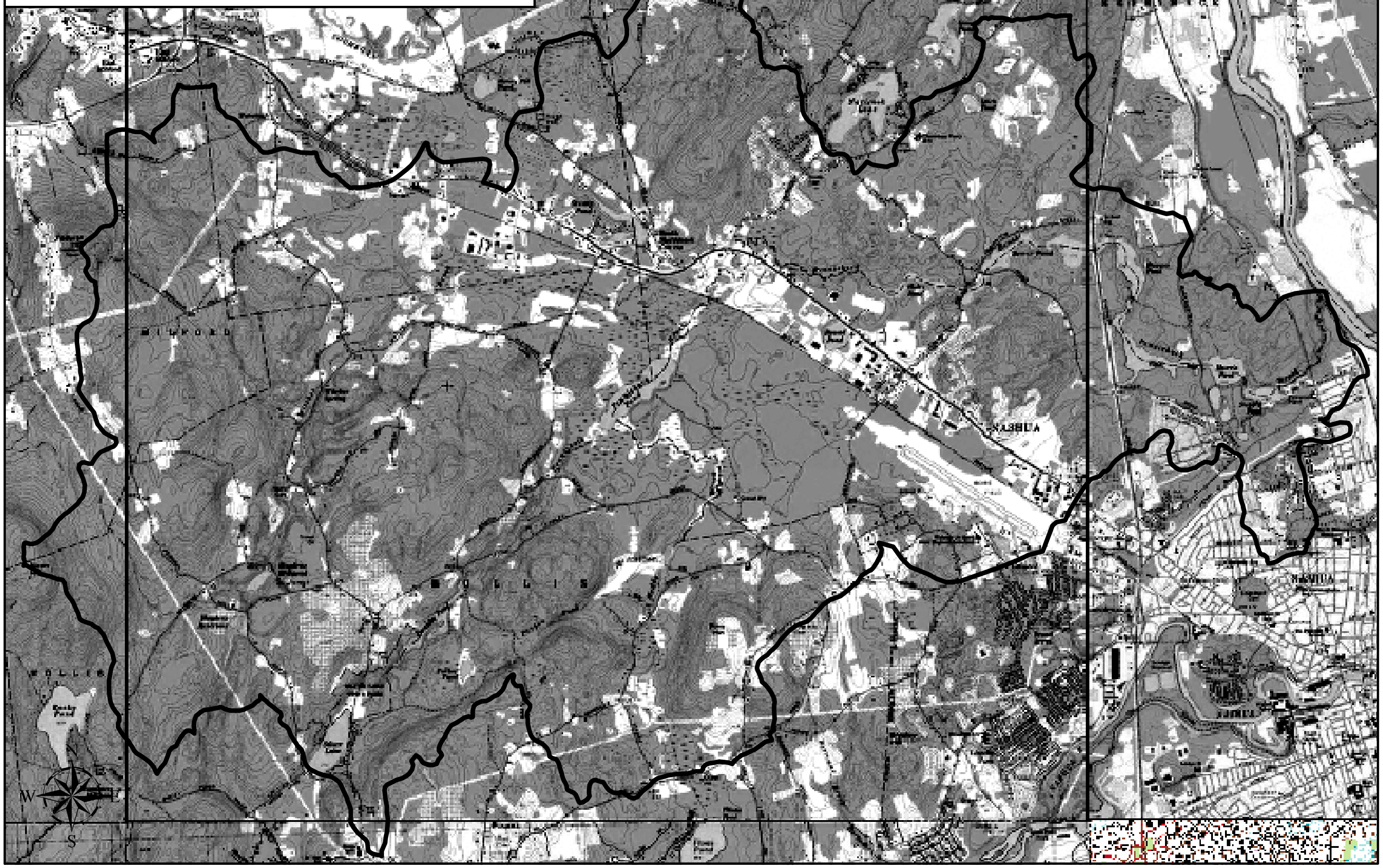


FIGURE 3-1: PENNICHUCK SUBWATERSHED MAP

Table 3-4: Subwatershed Input Data

Sub-watershed	Area (acres)	width (ft)	Max Elev. (ft)	Min Elev. (ft)	Slope (%)	Impervious (%)	N-Imperv	N-Perv	D-store Imp (in)	D-store Perv (in)	Sub-watershed
1	279	9,075	253	95	2.96%	29.38%	0.011	0.257	0.081	0.225	1
2	318	12,822	262	108	2.04%	34.03%	0.011	0.198	0.088	0.163	2
3	662	12,752	276	148	1.71%	40.72%	0.011	0.163	0.087	0.141	3
4	233	6,899	322	167	3.82%	64.39%	0.011	0.154	0.084	0.190	4
5	19	2,697	207	167	2.52%	17.57%	0.011	0.512	0.099	0.290	5
6	1,406	20,336	371	174	1.65%	32.83%	0.011	0.110	0.089	0.113	6
7	940	14,724	345	177	1.94%	55.30%	0.011	0.137	0.100	0.134	7
8	1,088	16,178	350	178	1.81%	34.89%	0.011	0.153	0.099	0.136	8
9	960	15,834	401	188	2.29%	36.38%	0.011	0.139	0.100	0.150	9
10	491	15,047	311	191	1.36%	14.97%	0.011	0.154	0.093	0.173	10
11	665	14,578	497	188	3.60%	17.58%	0.011	0.189	0.088	0.183	11
12	939	15,576	438	191	2.70%	9.36%	0.011	0.144	0.096	0.160	12
13	1,768	21,771	444	191	1.98%	8.49%	0.011	0.148	0.098	0.149	13
14	1,338	24,143	514	198	2.23%	11.89%	0.011	0.137	0.091	0.164	14
15	26	2,542	204	191	0.87%	7.48%	0.011	0.425	0.100	0.277	15
16	34	12,117	208	191	0.24%	25.62%	0.011	0.170	0.086	0.243	16
17	1,373	19,548	405	191	1.86%	22.69%	0.011	0.194	0.099	0.220	17
18	951	19,161	512	191	2.85%	27.98%	0.011	0.223	0.098	0.242	18
19	337	14,483	519	201	3.73%	16.15%	0.011	0.196	0.098	0.184	19
20	686	16,283	421	201	2.30%	25.89%	0.011	0.192	0.100	0.192	20
21	105	6,299	301	201	2.70%	41.20%	0.011	0.294	0.099	0.242	21
22	1,326	19,218	602	208	3.49%	9.68%	0.011	0.210	0.100	0.215	22
23	1,686	19,957	601	259	2.91%	9.30%	0.011	0.217	0.099	0.214	23
24	741	12,229	582	220	5.03%	11.53%	0.011	0.189	0.100	0.219	24

FIGURE 3-2: PENNICHUCK SUBWATERSHED
USGS TOPOGRAPHICAL MAP



cover assessment (GRANIT, 2001) was not used because many developed areas were classified as a type of wooded area based on the many trees and semi-developed adjacent land. The NRPC land use layer (NRPC, 2005) is used because it most accurately represents land use within the watershed.

NRPC maintains a land use database for each of the communities in the Pennichuck watershed. The land use layer is delineated by each parcel (Figure 1-2). Therefore, the remaining land not in a parcel was defined as a road land use. Typically, a land use includes the corresponding roadways within its extents. Because of this, the model runoff coefficients will differ from typical values because much of the impervious area has been detached from the land use.

Some error in the land use layer exists because of the fact that it is parcel-based. An instance of this error is a commercial parcel that is 50% undeveloped. This error will cause the runoff and pollutant coefficients to be less than expected, similar to the road concept stated above. Because this type of error is consistent throughout the watershed it is assumed that it will not negatively affect the results of the model; however, this does limit the ability to compare modeled values to typical values from other models.

Pervious and Impervious Areas

Pervious areas, unpaved and unbuilt land, and impervious areas are defined and modeled separately. Table 3-5 defines these remaining subwatershed inputs.

Table 3-5: Pervious and Impervious Area Parameters (Rossman, 2005)	
Parameter	Definition
Percent Impervious	Percent of land area which is impervious
N-Impervious	Manning's n for overland flow over impervious areas
N-Pervious	Manning's n for overland flow over pervious areas
Dstore-Impervious	Depth of depression storage on impervious areas
Dstore-Pervious	Depth of depression storage on pervious areas
% Zero-Impervious	Percent of impervious area with no depression storage
Subarea Routing	Choice of internal routing, impervious runoff to pervious, pervious runoff to impervious, or runoff from each directly to outlet

Adapted from SWMM Version 5.0 Manual (Rossman, 2005)

The land use types obtained from NRPC were consolidated into the eight land use types shown in Table 3-6. The percent impervious area within each land use type was estimated as a composite value of the respective land uses. The water land use represents streams, ponds and reservoirs and was assumed to be 100% impervious because precipitation falling onto this surface type is directly available in the stream or pond. To estimate flow times across the subwatershed areas, Manning's n roughness coefficient (American Society of Civil Engineers, 1982) needs to be defined for both impervious and pervious areas. Since most impervious areas are paved with asphalt, a constant Manning's n value of 0.011 was used (Schwab, Fangmeier, Elliot, and Frevert, 1993). The pervious areas within developed areas are typically lawn or landscaped areas. Therefore a constant Manning's n value of 0.017 for cultivated soils with greater than 20% residue cover was assigned to each of these pervious areas (McCuen, Johnson and Ragan, 1996). A separate depression storage value, the amount of rainfall retained before runoff begins, is required for pervious and impervious areas. A constant depression storage coefficient of 0.05 inches was assigned to each impervious area except for streams, ponds, and reservoirs that were assumed to be

Table 3-6: Landuse Types and Parameters

NRPC Landuse	Model Landuses	Impervious	D-store Perv.	D-store Imp.	N-Pervious	N-Impervious
Agricultural	Open Space	1%	0.2	0.05	0.17	0.011
Commercial	Commercial	83%	0.1	0.05	0.17	0.011
Industrial	Industrial	50%	0.1	0.05	0.17	0.011
Institutional	Commercial	83%	0.1	0.05	0.17	0.011
Manufactured Housing	Low Density Residential	15%	0.25	0.05	0.17	0.011
Mixed Use	High Density Residential	44%	0.2	0.05	0.17	0.011
Multi Family Residential	High Density Residential	44%	0.2	0.05	0.17	0.011
Municipal Facility	Commercial	83%	0.1	0.05	0.17	0.011
Permanent Open Space	Forest	1%	0.3	0.05	0.60	0.011
ROW	Open Space	1%	0.2	0.05	0.17	0.011
Recreation	Forest	1%	0.3	0.05	0.60	0.011
Road	Road	66%	0.2	0.05	0.011	0.011
School	High Density Residential	44%	0.2	0.05	0.17	0.011
Single Family Residential	Low Density Residential	15%	0.25	0.05	0.17	0.011
Vacant	Forest	1%	0.3	0.05	0.60	0.011
Water	Water	100%	N/A	0	N/A	0.011

impervious areas. A depression storage of 0.0 inches was assigned for these areas. The pervious area depression storage values were estimated for each land use type from Table 3-7 adapted from the SWMM Manual (Rossman, 2005). A composite of these values was used for each subwatershed.

Table 3-7: Typical Depression Storage Values	
Impervious surfaces	0.05 - 0.10 inches
Lawns	0.10 - 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

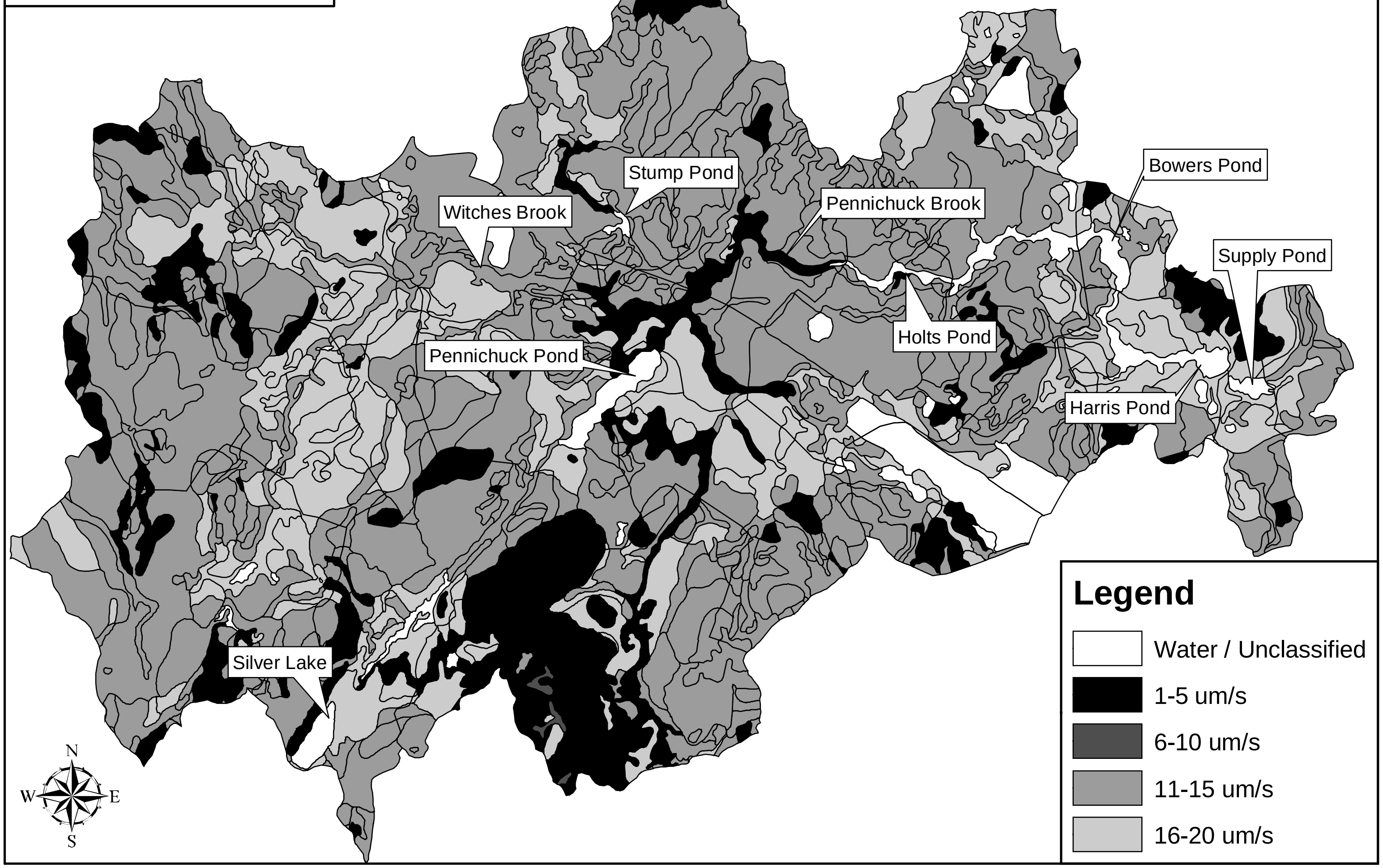
Source: (ASCE, 1992)

The default value of 25% of impervious areas with zero depression storage was used for the model. Many roads and parking lots have drainage pipes discharging runoff directly to the nearest waterbody. For all subwatersheds, half of the runoff from the impervious areas discharges directly to the downstream segment and half is routed onto the pervious area where a portion of it can be infiltrated if capacity exists. This is because many of the roads and parking lots have a direct discharge to nearby surface waters while other have no collection system and drain over vegetated areas.

Soils Data and Infiltration Parameters – Pervious Areas

The New Hampshire soils layers are delineated within each county. The soils layer for Hillsboro County East was correlated to adjacent counties in February 1980 (GRANIT, 2006b). The soils database identifies the soil type by hydrologic group (Figure 3-3) and provides the infiltration rates for each soil type (NRCS, 2001). The soils throughout the project area are predominantly loamy sand and sandy loam. The soils database includes maximum and minimum permeability rates for each soil type. These values correspond to the layer within any horizon of the soil that has the

FIGURE 3-3: PENNICHUCK WATERSHED SOILS MAP



maximum or minimum infiltration rate. For the purposes of this model, it was assumed that the maximum infiltration rate was the top layer and the minimum infiltration rate was the lowest layer. The maximum permeability rate was set as the maximum infiltration rate for the Horton Equation (Rossman, 2005) which represents the initial infiltration capacities of the upper sandy soil layers. During a storm event, the soils will be able to absorb more precipitation initially which will then decline to a minimum infiltration rate. The minimum permeability rate, the saturated hydraulic conductivity, was input as the minimum infiltration rate (Table 3-8). The infiltration rate during the remainder of storm events following the initial high infiltration rates is controlled by the soils layer with the slowest infiltration rate. When these infiltration rates are compared to typical values, they far exceed those published in the SWMM manual for their hydrologic group. This would appear problematic, but during field data collection and occasional visits within the watershed many existing detention basins produced little or no runoff for small to medium size storms. This demonstrates that the infiltration capacitiy of the local soils is quite high making these values seem reasonable. Therefore, the infiltration rates were used without modification.

In addition to the above parameters, the model requires the decay constant for the Horton curve which adjusts the model from using the maximum infiltration rate to the minimum infiltration rate. The alpha value was initially estimated at four per hour for all subcatchments (Table 3-9). The drying time for a soil to regain its initial infiltration capacity was assumed to be five days for all subwatersheds. Horton's equation also allows the user to enter a maximum infiltration volume for a soil. No

Table 3-8: Soils Properties Input Data					
Sub-watershed	Maximum Infiltration Rate (in/hr)	Minimum Infiltration Rate (in/hr)	Decay Rate Constant	Drying Time	Maximum Infiltration Volume
1	4.000	1.506	4	5	0
2	4.114	1.297	4	5	0
3	3.459	1.157	4	5	0
4	3.747	1.389	4	5	0
5	5.487	1.843	4	5	0
6	3.712	1.256	4	5	0
7	2.506	0.731	4	5	0
8	3.503	1.327	4	5	0
9	3.369	1.126	4	5	0
10	3.502	1.294	4	5	0
11	3.297	1.055	4	5	0
12	3.876	1.108	4	5	0
13	2.567	0.758	4	5	0
14	3.304	0.757	4	5	0
15	3.266	1.029	4	5	0
16	3.399	1.457	4	5	0
17	3.507	1.128	4	5	0
18	3.968	1.383	4	5	0
19	4.712	1.303	4	5	0
20	4.476	1.271	4	5	0
21	4.968	1.510	4	5	0
22	3.950	0.896	4	5	0
23	3.751	0.833	4	5	0
24	3.472	0.773	4	5	0

maximum infiltration volume was set for all subwatersheds due the high infiltration rates encountered.

Table 3-9: Decay Rate of Infiltration Capacity	
α value (per hour)	Percent of decline of infiltration capacity towards limiting value after 1 hour
2	76
3	95
4	98
5	99

Adapted from EPA SWMM 5.0 Manual (Rossman, 2005)

<u>*Groundwater Flow and Aquifer Parameters*</u>

To facilitate model calibration, homogeneous aquifers were assumed. The only parameters which varied between the aquifer input parameters were the beginning water table elevation, the ground surface elevation and the respective receiving node invert. An average of the porosity, wilting point and field capacity were estimated at 0.44, 0.066, and 0.15 in. respectively (Rawls, Brakensiek and Miller, 1983).

The model varies the hydraulic conductivity and soil tension based on the soil moisture content. No site specific data was available for this input. The slope of these lines were estimated from (Laliberte, Corey and Brooks, 1966) for Columbia Sandy Loam.

A total of 16 aquifers were specified to provide groundwater interactions within the model (Figure 3-4). Table 3-10 summarizes the aquifers and their properties. The starting elevation for each aquifer was set at the invert of the receiving node. The coefficient and exponent within the groundwater flow equation were estimated using the measured flow data from monitoring location T-7. The average flow at this site was approximately 30 cfs. The drainage area, consisting of

FIGURE 3-4: PENNICHUCK AQUIFER MAP

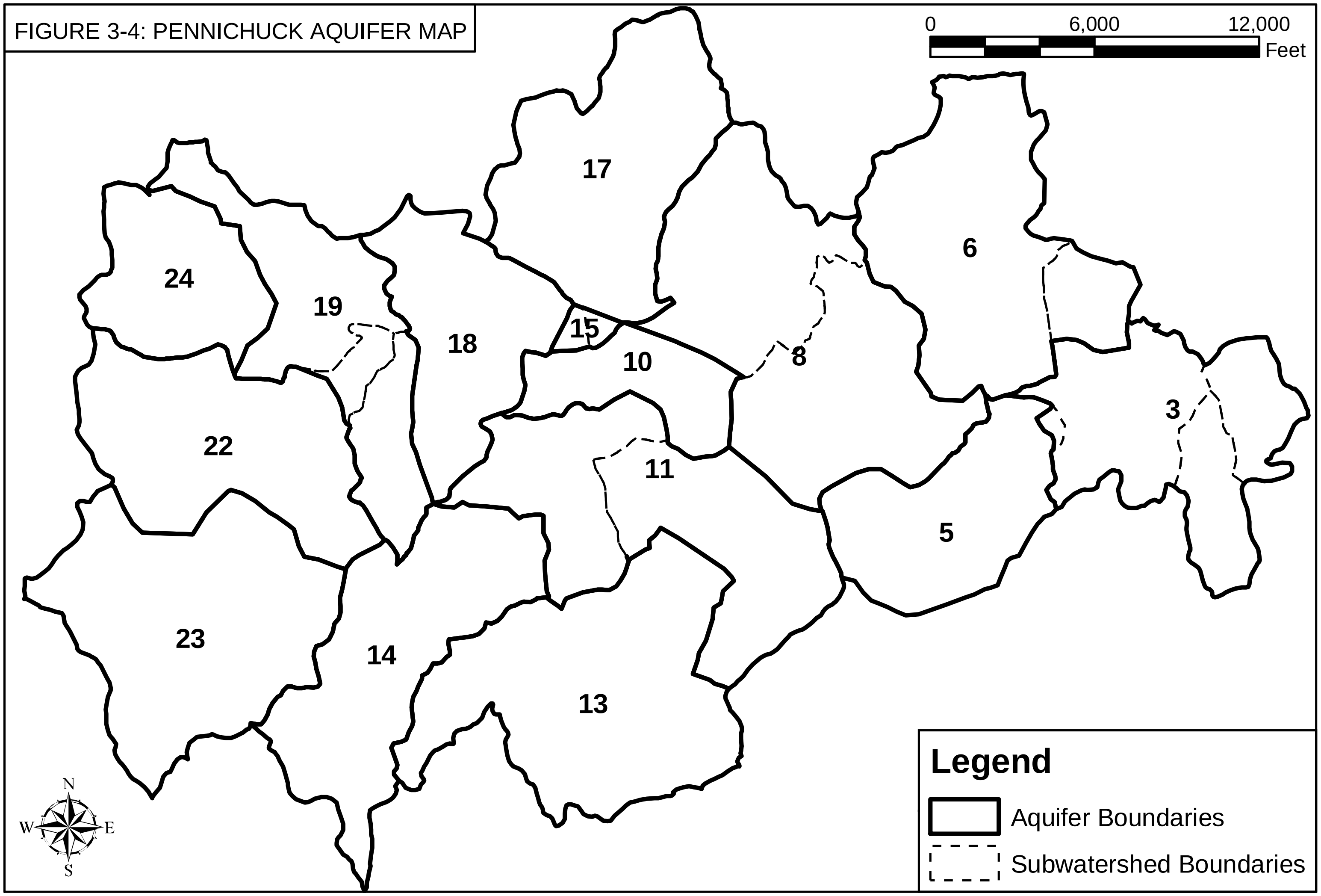


Table 3-10: Groundwater Flow Properties

Sub-watershed	Aquifer Name	Outlet Node	Surface Elevation (ft)	GW Flow Coeff. A1	GW Flow Exp. B1	SW Flow Coeff. A2	SW Flow Exp. B2	Surface-GW Interaction Coefficient A3	Fixed SW Depth (ft)
1	N/A	N/A							
2	N/A	N/A							
3	N/A	N/A							
4	6	Bowers Pond	171	0.0115	2	0	1	0	0
5	N/A	N/A							
6	6	Bowers Pond	171	0.0115	2	0	1	0	0
7	5	T-1	180	0.0115	2	0	1	0	0
8	8	Holts Pond	179.46	0.0115	2	0	1	0	0
9	8	Holts Pond	179.46	0.0115	2	0	1	0	0
10	10	T-3	193	0.0115	2	0	1	0	0
11	11	Pennichuck Pond	194	0.0115	2	0	1	0	0
12	11	Pennichuck Pond	194	0.0115	2	0	1	0	0
13	13	T-9	195	0.0115	2	0	1	0	0
14	14	T-8	201	0.0115	2	0	1	0	0
15	15	Junction 1	195	0.0115	2	0	1	0	0
16	15	Junction 1	194	0.0115	2	0	1	0	0
17	17	T-4	194.75	0.0115	2	0	1	0	0
18	18	T-5	195	0.0115	2	0	1	0	0
19	19	T-6	204	0.0115	2	0	1	0	0
20	19	T-6	204	0.0115	2	0	1	0	0
21	19	T-6	204	0.0115	2	0	1	0	0
22	22	T-7	211	0.0115	2	0	1	0	0
23	23	NRPC-8	225	0.0115	2	0	1	0	0
24	24	NRPC-7	223	0.0115	2	0	1	0	0

subwatersheds 21, 22, and 23, is 3117 acres. Assuming a one foot rise in the water table contributes this flow, the coefficient was estimated as 0.0096 to accommodate for the units of cfs/acre. The flow exponent was set to one to provide a linear flow curve.

Tributary and Pond Data

To route runoff and baseflow through the model one must determine the physical characteristics of the streams and surface waters. Very little information is available on the streams and conducting a full scale survey to obtain the elevations and cross-sections of the length of the streams would be very time consuming and require permission to access many properties. Cross-sections of the streams are available for the stream gaging locations described further in Chapter 4. Streams were assigned a typical stream channel with a flat bottom and one to one side slopes. Bottom widths varied based on measurements from the streamflow determinations and field observations. Stream widths varied between ten and thirty-five feet. Stream elevations at each node were estimated from Figure 3-2. In addition, based on field observations, these inputs were adjusted to match actual conditions.

Bathymetric data

In 2000, Comprehensive Environmental Inc. conducted a sediment study of the Pennichuck Ponds (CEI, 2000). This study included bathymetric data for each of the reservoirs. This bathymetry was used to calculate the existing water storage capacity of each reservoir (Appendix D). Where available, actual spillway elevations were used. In cases where this data was not available, USGS topographic maps were used to approximate the elevation. The reservoirs were modeled as having their respective surface area and an average depth based on storage capacity. Where existing spillway measurements were not available, the parameters were adjusted in model calibration to best match the measured flow data.

CHAPTER 4

FLOW MONITORING AND DATA COLLECTION

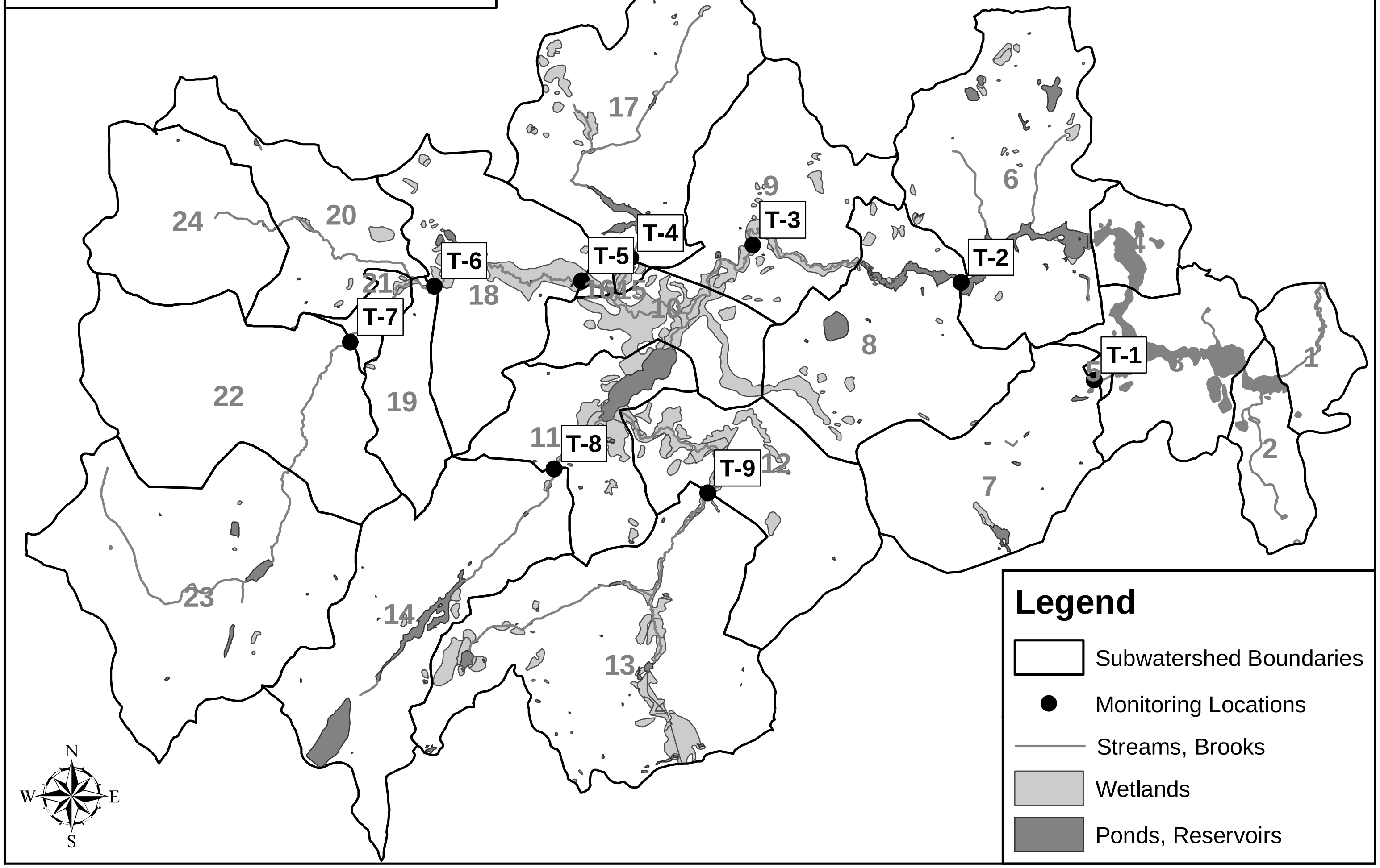
Stream Data Collection

Stream Levels

The nine flow monitoring locations, T-1 through T-9, were previously determined by CEI to obtain an overall understanding of runoff throughout the watershed. These locations were established to use existing sites and to spread the monitoring locations throughout the watershed (Figure 4-1). This allowed different areas of the watershed to be compared, (ie. rural to urban areas). Initially, a United States Geological Survey (USGS) style C staff gage was installed at each location. This type of staff gage comes in 3 1/3 foot sections and is marked at every foot, tenth of a foot, and hundredth of a foot. The staff gages were installed during lower flow periods, and were secured to concrete structures where possible. Alternatively, the gages were secured to five-foot steel stakes installed at the edge of the stream bank. Since streams often fluctuate in level greater than the span of the gage, the gages were installed to guarantee that readings could be obtained during low flow periods.

Using the readings obtained from the staff gages to determine streamflow is not ideal because they are from one instantaneous point in time. Streamflows are actually dynamic and are always changing according to dry spells and precipitation. Therefore, water level transducers with dataloggers were installed at each of these nine locations during September and October 2005. The Model WL15X dataloggers (Global Water Instrumentation, 2002) are capable of reading depths from zero to fifteen inches. The transducer and datalogger are built into the unit and the data can be

FIGURE 4-1: STREAMFLOW MONITORING LOCATIONS MAP



retrieved using any computer or laptop with basic software. The dataloggers can retain 24,000 readings (Global Water Instrumentation, 2002), virtually eliminating data loss due to overwriting existing data on the unit. The dataloggers are vented which provides automatic barometric pressure compensation to prevent reading errors.

As shown in Figure 4-2 the datalogger units were installed using two-inch schedule 40 pvc pipe as an outer casing to protect them. The bottom twelve inches of the pipe has several ¼" diameter holes drilled to make sure the water level in the casing was the same as in the stream. The sensor was secured to the side of the pvc pipe and the pvc pipe was set to keep the sensor at a similar level to the bottom of the staff gage (just above the lowest part of the stream channel). The end of the datalogger with the communication port was left at the top of this pvc pipe (if it was high enough) or it was installed at a higher elevation in another short two-inch pvc pipe. These were either buried for protection or secured to the guardrail. These dataloggers were set to record water levels every 30 minutes. The data was then retrieved every few months while inspecting the dataloggers.

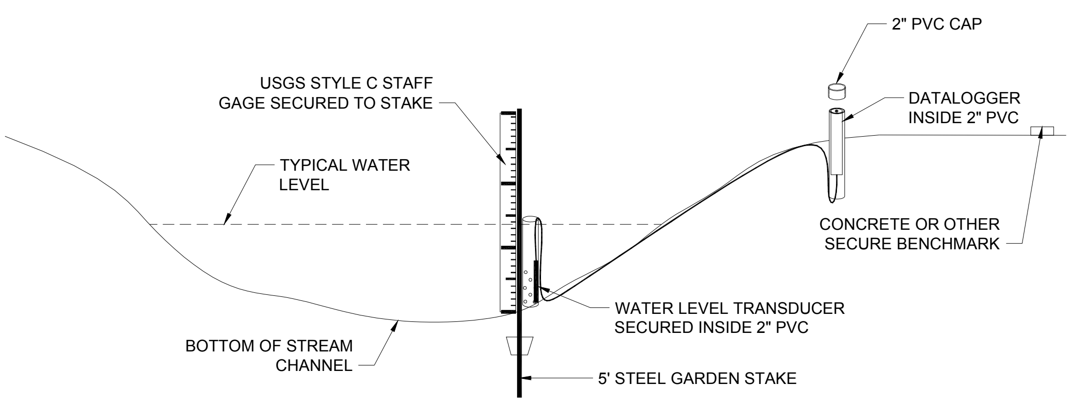


FIGURE 4-2: TYPICAL DATALOGGER INSTALLATION

Stream Cross-Sections

The stream bottom cross-section was surveyed using a laser level with ¼" accuracy at 100 feet. The stream bottom was broken up into discrete segments and the elevation of each was recorded. A measuring tape was permanently installed at each site to identify where each of these depths were recorded (Appendix F). Each interval was marked with ribbon or tape for future reference to expedite streamflow measurements. The interval varied based on the width of the stream from about two feet to six inches. It would be ideal to obtain twenty or more discrete segments at each cross-section, but some locations have very small channel widths or culverts. At these locations, the cross-sections were bisected into 12" or smaller segments (Figure 4-3) (Division of Watershed Management (DWM), 2003). A few locations included culverts where only the invert elevation and diameter of the culvert were recorded. The staff gage, water level, and bench mark were surveyed as well. The datalogger water level was also recorded during surveying which allowed staff gage readings and/or datalogger readings to be correlated to the geometry of the stream channel.

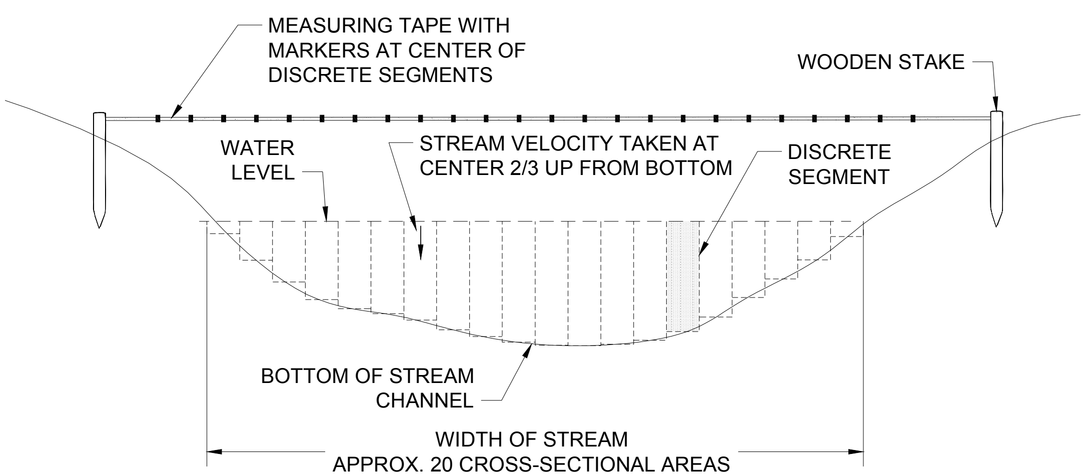


FIGURE 4-3: STREAM CROSS-SECTION DISCRETIZATION

Stream Velocities

Stream velocities were measured at each location where the stream elevation was recorded. The stream velocities were measured using a Marsh McBirney 2000 Flo-Mate velocity meter (Marsh-McBirney Incorporated, 1990) (Appendix G). A typical flow meter with a propeller could not be used because of the low velocities associated with many of these streams during low flow. The flow meter used has a range of –0.5 to +19.99 ft/sec which is consistent with the observed stream velocities (Marsh-McBirney Incorporated, 1990). Full waders were necessary because of the water depth at some sites. Velocities were recorded by standing downstream of the meter and holding it approximately 2/3 up from the bottom of the stream (Marsh-McBirney Incorporated, 1990). Once the velocity stabilized on the meter, the velocity was recorded. This was repeated at each interval at each site. Three to five stream velocity rounds were completed at each site during different stream levels.

Field Difficulties

Two installation trips were required to install all nine dataloggers. At two adjacent sites, the cord to the datalogger was severed multiple times. Based on the cut marks of the datalogger and the location on the cord, it appears as though an animal had bitten the cord each time. It is believed that the culprit was one or more beavers living in the area.

At monitoring location T-4, the streamflows were not consistent with the results of the upstream and downstream streamflows. This site was located at a railroad bridge with a deep flow path. Some difficulties were experienced because of the supports holding up the bridge, but these were not believed to be a significant source of error. However, a dam located about 100 feet downstream, probably created by local wildlife, most likely caused some different flow patterns in the stream at this segment. Water height was controlled by the downstream dam and any change in the height of the dam made the calibration curve invalid. This site was moved several hundred feet downstream to a roadway bridge crossing. Here streamflows were measured that were consistent with the upstream and downstream measurements.

Streamflow Determinations

To allow for model calibration of runoff, streamflows were calculated at each of the nine newest sampling sites (Appendix F). The streamflows were determined according to the Massachusetts Department of Environmental Protection Division of Watershed Management Standard Operating Procedure (SOP) for Flow Measurement dated April 2003. The width of each segment is defined as "the cross-sectional area bounded on each side of the vertical velocity measurement by a distance halfway to the preceding vertical and halfway to the following vertical" (DWM, 2003). The stream channel was assumed to remain unchanged while the water level and velocities varied due to time. The depth of water at each segment and the width of each segment are used to determine the flow in each section. The total streamflow at each site is calculated using the summation of the flow in each segment (DWM, 2003).

Streamflows were measured three or more times during different stream stages. In order to convert the water levels to streamflow, a stage-discharge curve was developed. A unique curve was developed for each site linking stream levels recorded by the data logger to actual streamflows (Appendix I). Using Microsoft Excel 2002, the equation of a best-fit line was obtained for each site. The remaining water levels recorded at each site were then input into this equation to develop a continuous streamflow database (Appendix J). These flows were input into the model where they could be compared directly to modeled results.

CHAPTER 5

MODEL CALIBRATION & VALIDATION

Calibration Method

The flow data obtained during this project is the only available flow data for the watershed. The time period used for calibration was September 29, 2005 to February 1, 2006 with a few periods of missing information.

In order to calibrate the model, the model was run from April 1, 2005, until February 1, 2006. This allows the model to run for five months prior to the time period that was used for calibration to remove the effect of the initial conditions.

Typically, the subcatchment widths are the major flow calibration parameters. During initial model calibrations where the model did not include the aquifer component, subcatchment widths were adjusted to unreasonably low values (approximately 10% of the estimated value). The aquifer component was then incorporated into the model to provide baseflow. The model predicts the primary source of flow to the streams to be via the aquifers as groundwater flow both during storm events and as baseflow. The subcatchment widths were adjusted during calibration procedures but exhibited little to no effect on the new model results. Therefore, these widths were all left as initially estimated. Because the primary source of flow is from groundwater, the groundwater interaction equation became the source of the key calibration parameters. This includes the groundwater flow coefficient and exponent. The model assumes that the aquifers are homogeneous throughout each subwatershed. These parameters were adjusted uniformly to calibrate the model to the measured streamflows.

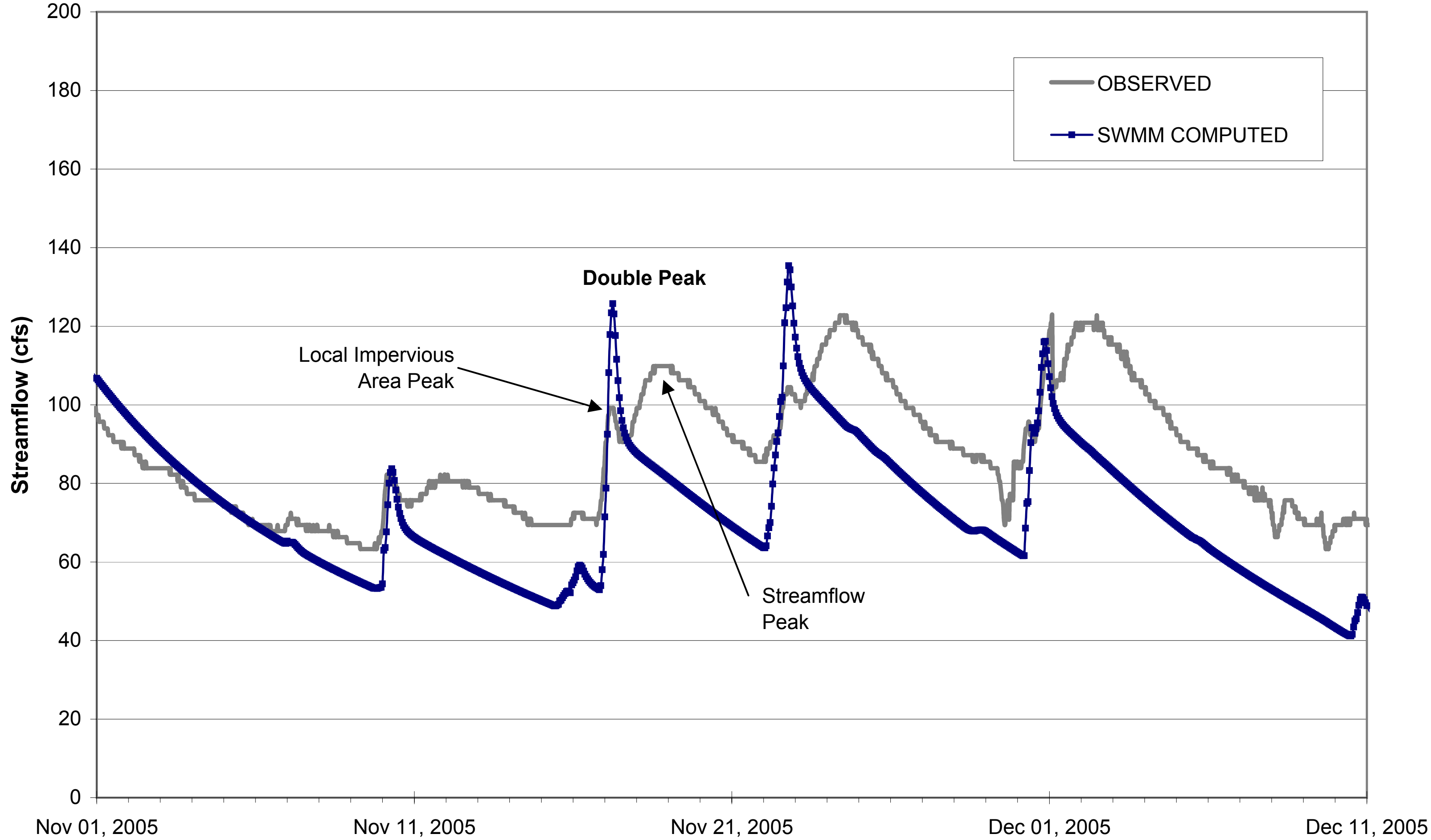
Calibration Results

Calibrating the model required trying to match peak flows during storm events as well as the recession curve during and after the storm event. This was difficult because there did not seem to be enough water available to match either or both of these. A quick estimation of the total streamflow at the lowest-most monitoring location compared to the total amount of precipitation reveals 1.50 billion cubic feet of water as streamflow compared to 1.66 billion cubic feet of precipitation. This reveals a streamflow to precipitation coefficient of 0.90. This indicates that evapotranspiration and other water losses should account for only 10% of the precipitation to the watershed. This is not consistent with typical evapotranspiration rates for the area which are about 20 inches (Randall, 1996).

The missing water could be a result of baseflow to the watershed resulting from areas outside of watershed/aquifers that were modeled. The size of the aquifers were determined solely based on the subwatershed drainage areas. In the field, this could be drastically different and potentially significant amounts of water could be flowing into the aquifers from adjacent watersheds/aquifers. Therefore the lack of evapotranspiration compared to total streamflow in the model was ignored.

The monitoring location at Holts Pond (T-2) indicates a double peaking action (Figure 5-1). This is most likely a result of the urbanized area adjacent to Pennichuck Brook in the lower portions of the watershed. These impervious areas create a quick peak due to their very short time of concentration. The primary contribution from the remaining parts of the watershed show a lag as a result of initial infiltration and travel time both through the subcatchment area and stream channels. This delay in the peak

Figure 5-1: Monitoring Location T-2 Streamflow Calibration Curve



is nearly 2 days indicating that the slowing mechanism is groundwater flow. The model predicts a single peak slightly larger than the double peaks shown in the streamflows. The lack of a double peak is indicative of a lack of travel time as the precipitation percolates into the groundwater and ultimately flows to the stream. Groundwater flow rates are typically orders of magnitude lower than surface water flows.

Monitoring stations T-1 and T-8 do not have significant contributions from baseflow. The cause of this appears to be different for each of these sites. The watershed for T-1 consists of a lot of impervious area from the predominantly commercial strip along Route 101a and the Nashua Airport. Based on typical values for land uses, the modeled impervious area is 6.74%. This watershed has an impervious fraction closer to 20%. This impervious area may be decreasing baseflow to the stream. Alternatively, groundwater may be flowing to adjacent streams transferring water out of this watershed. The aquifer component was removed from this subwatershed which provides a much closer match to the streamflow measurements (Figure 5-2). It is unknown why Station T-8 streamflow records do not show a consistent baseflow. The model is predicting the timing of the peaks but is over-estimating the flows during these periods and the recession after the peak (Figure 5-3).

The model is predicting flows quite well throughout the watershed as a whole, with the exception of over-estimating flows at some monitoring locations and underestimating flows in the western part of the watershed. Figure 5-4 plots calculated values from the model to observed values. The correlation coefficient of the model

Figure 5-2: T-1 Streamflow Calibration/Validation Curve

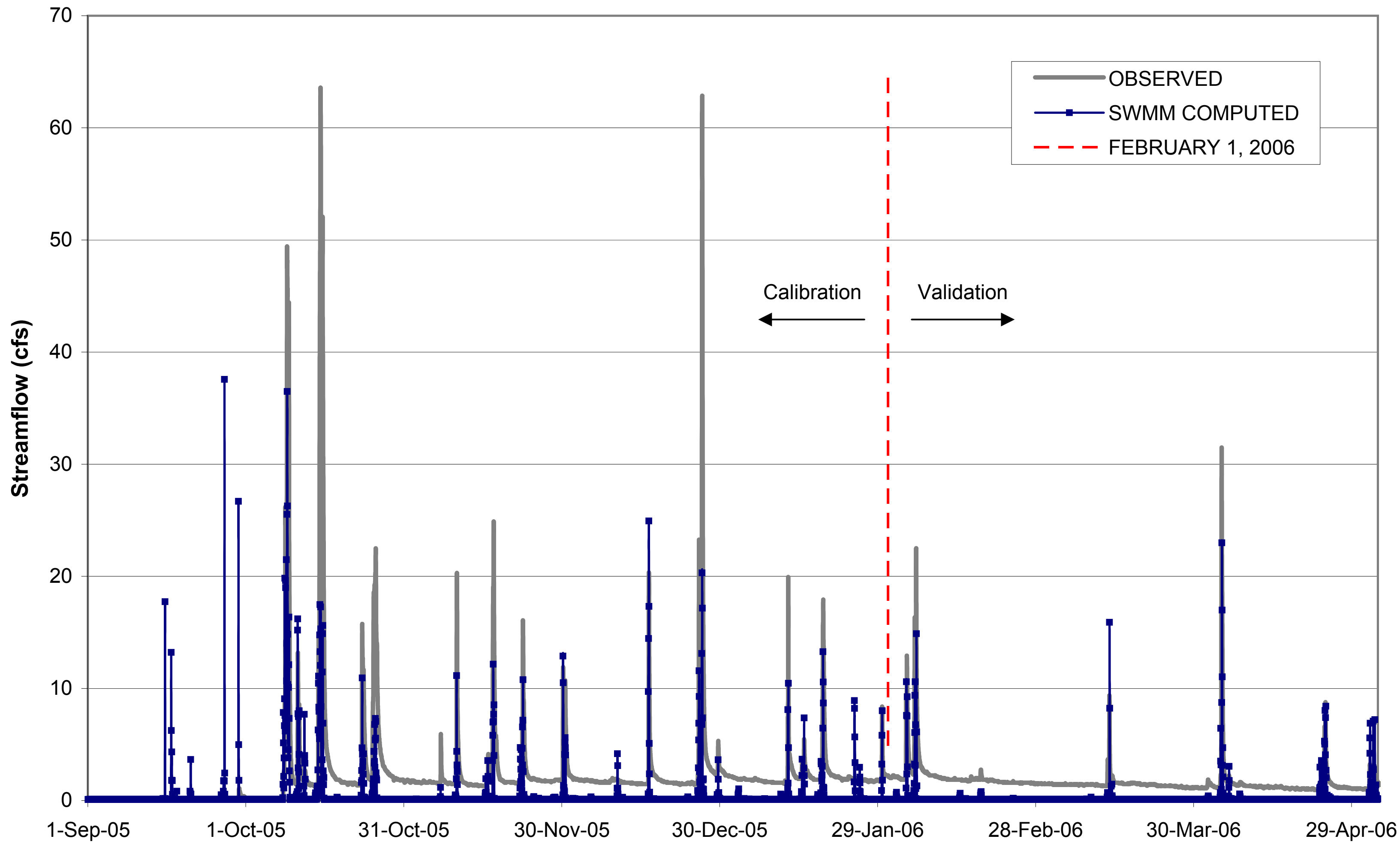


Figure 5-3: T-8 Streamflow Calibration/Validation Curve

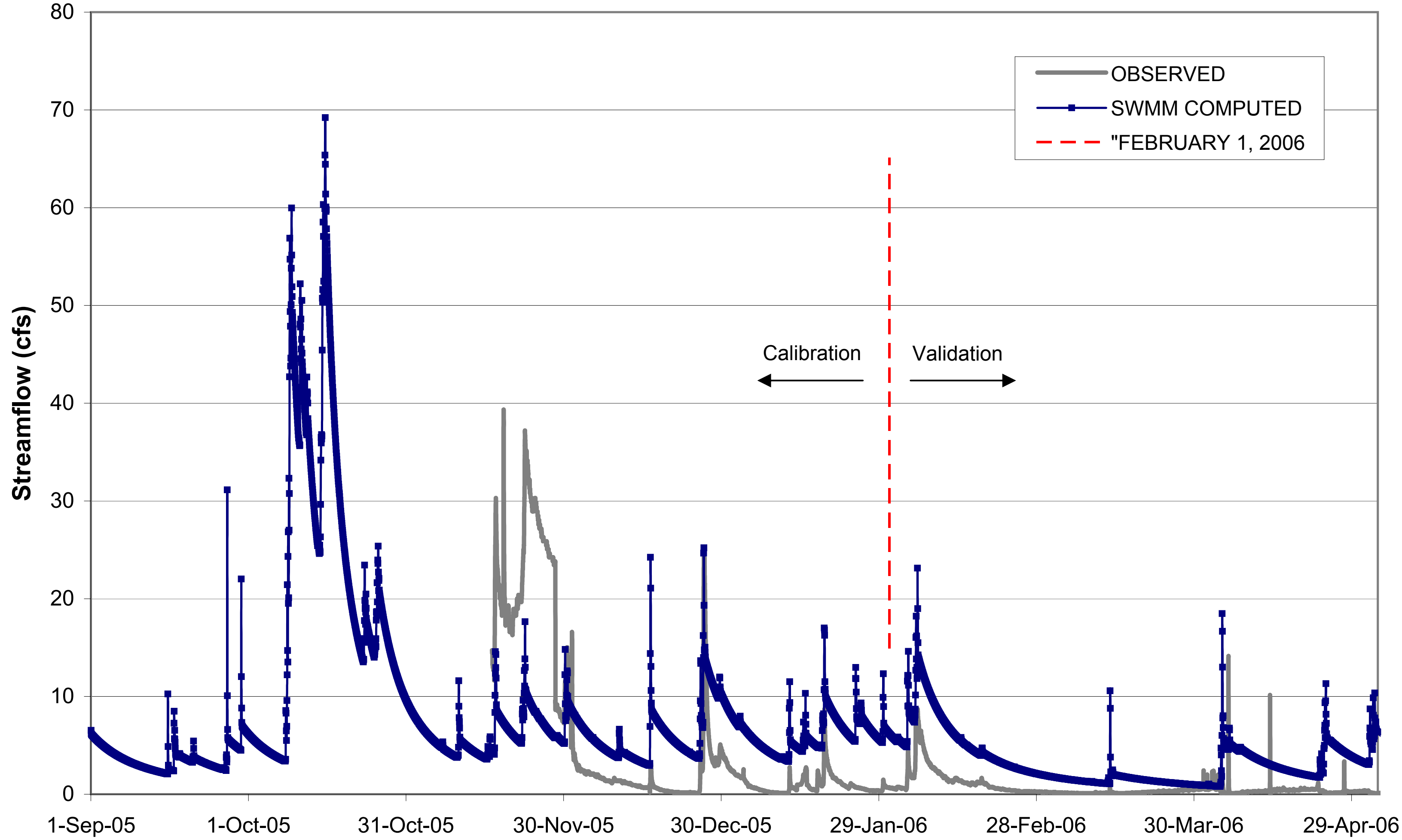
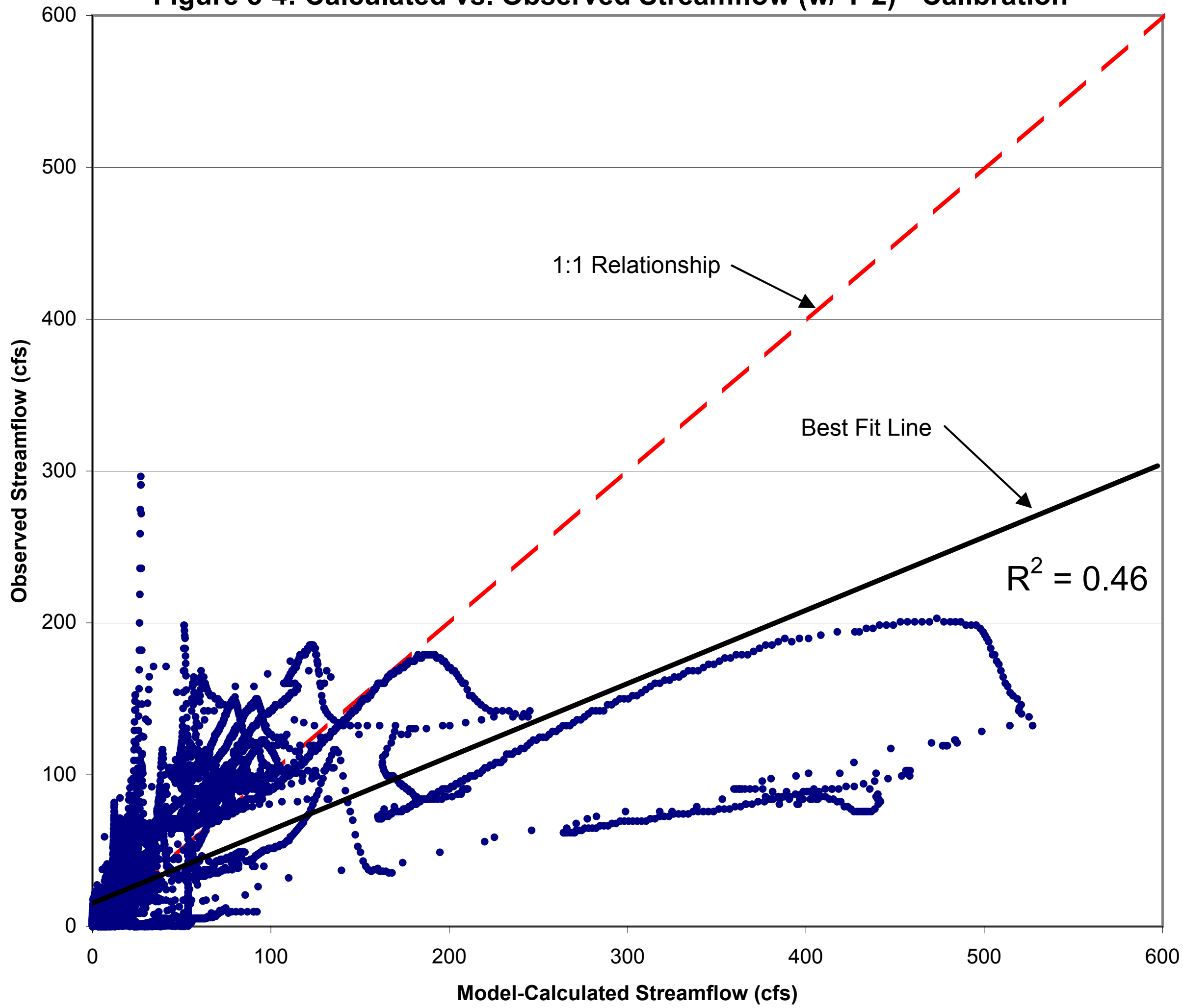


Figure 5-4: Calculated vs. Observed Streamflow (w/ T-2) - Calibration



based on this hourly data is 0.68. The coefficient of determination (R^2) is 0.46. As seen on Figure 5-5, high flows associated with extreme precipitation events in October 2005 were not modeled very accurately. This created a very large discrepancy for a best fit line from a one to one relationship. The majority of this error is amplified at monitoring location T-2. Therefore, a new plot of the calculated vs. observed values was produced excluding T-2 (Figure 5-6). Without these streamflows, the correlation coefficient is 0.71 and the R^2 is 0.50. A best fit line was applied to this dataset which more closely resembles a one to one relationship.

The standard error when excluding streamflows from T-2 is reduced from 26 cfs to 12 cfs. This error still appears to be quite large when compared to individual streamflows. The sum of the residual error accounts for only about 0.1% of the total streamflows measured in the watershed. This indicates that although the accuracy of the timing of streamflows could be improved, the overall runoff and streamflow volumes are very accurate.

Model Validation

Model validation was accomplished using streamflow data from February 1, 2006 to May 4, 2006. The purpose of this is to confirm that the calibrated model is accurately predicting runoff in the watershed during different time periods. The model was run from April 2005 to May 2006.

Several of the stream monitoring locations did not have complete records during the validation time period. All monitoring locations even with incomplete records except T-6 were used for model validation. T-6 was not used solely because no streamflow data was measured at this site during the validation period. This

Figure 5-5: Calculated vs. Observed Streamflow (w/o T-2) - Calibration

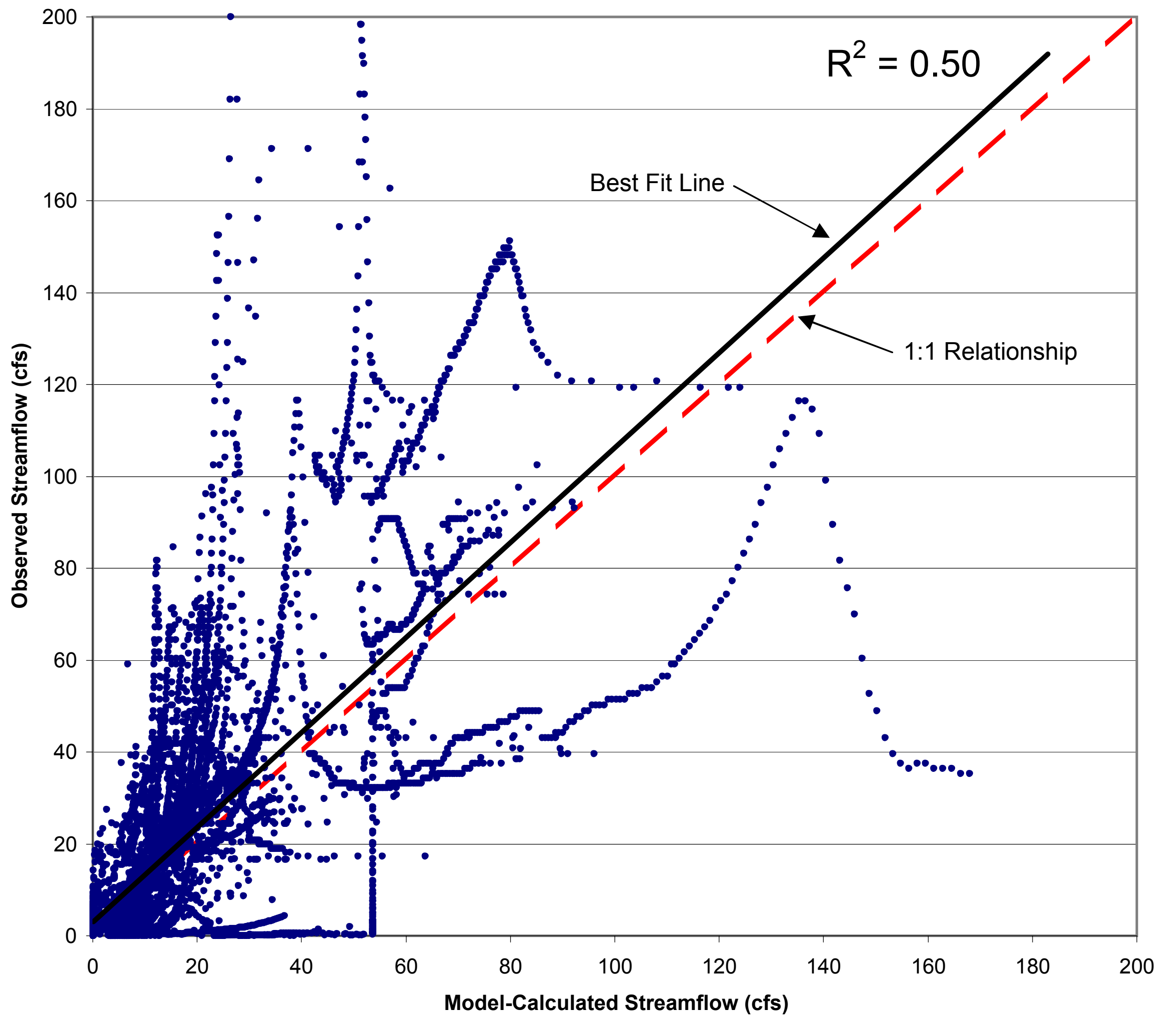
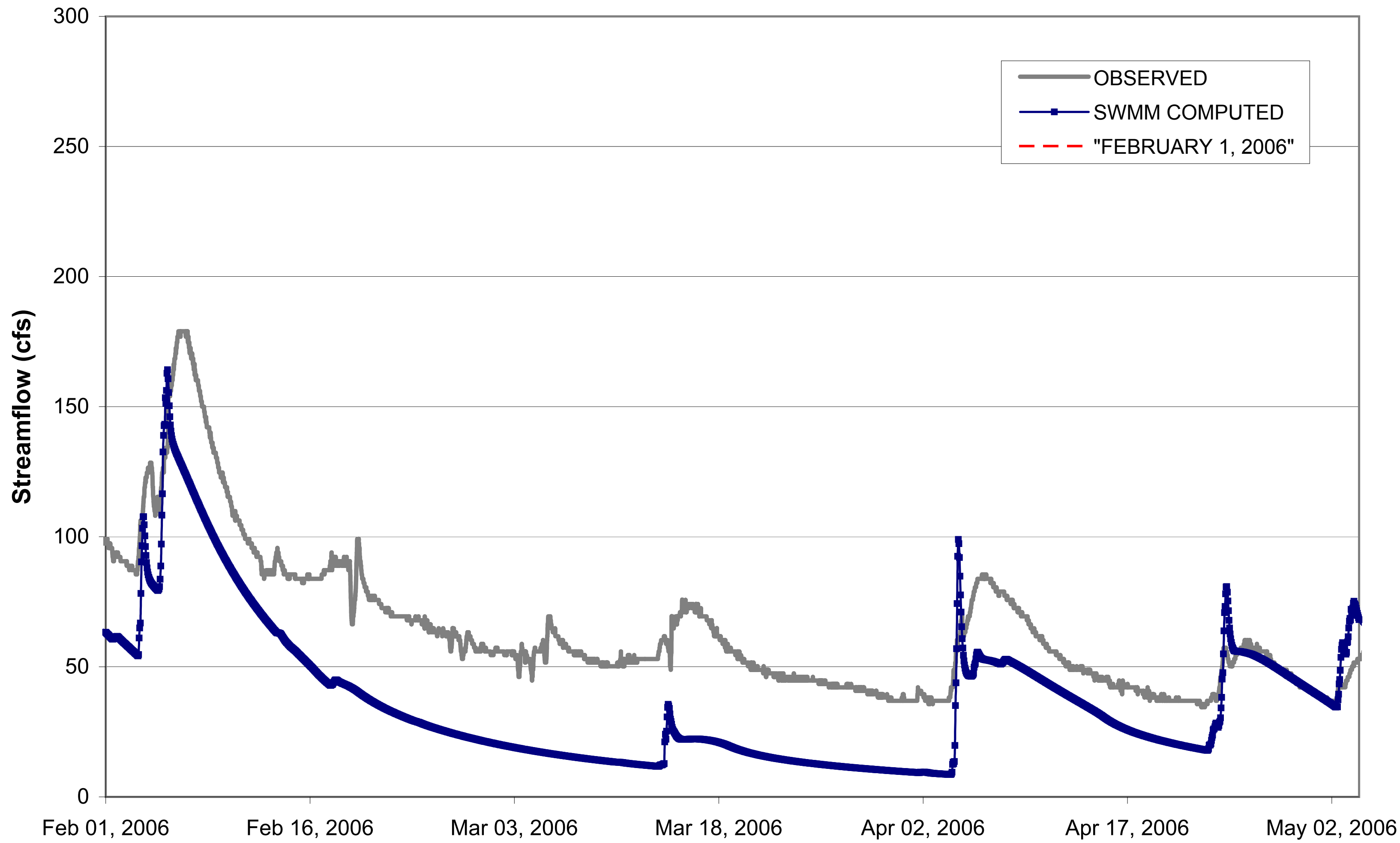


Figure 5-6: T-2 Streamflow Validation Curve



location is at the center of the watershed and therefore is partially accounted for by several of the other stations.

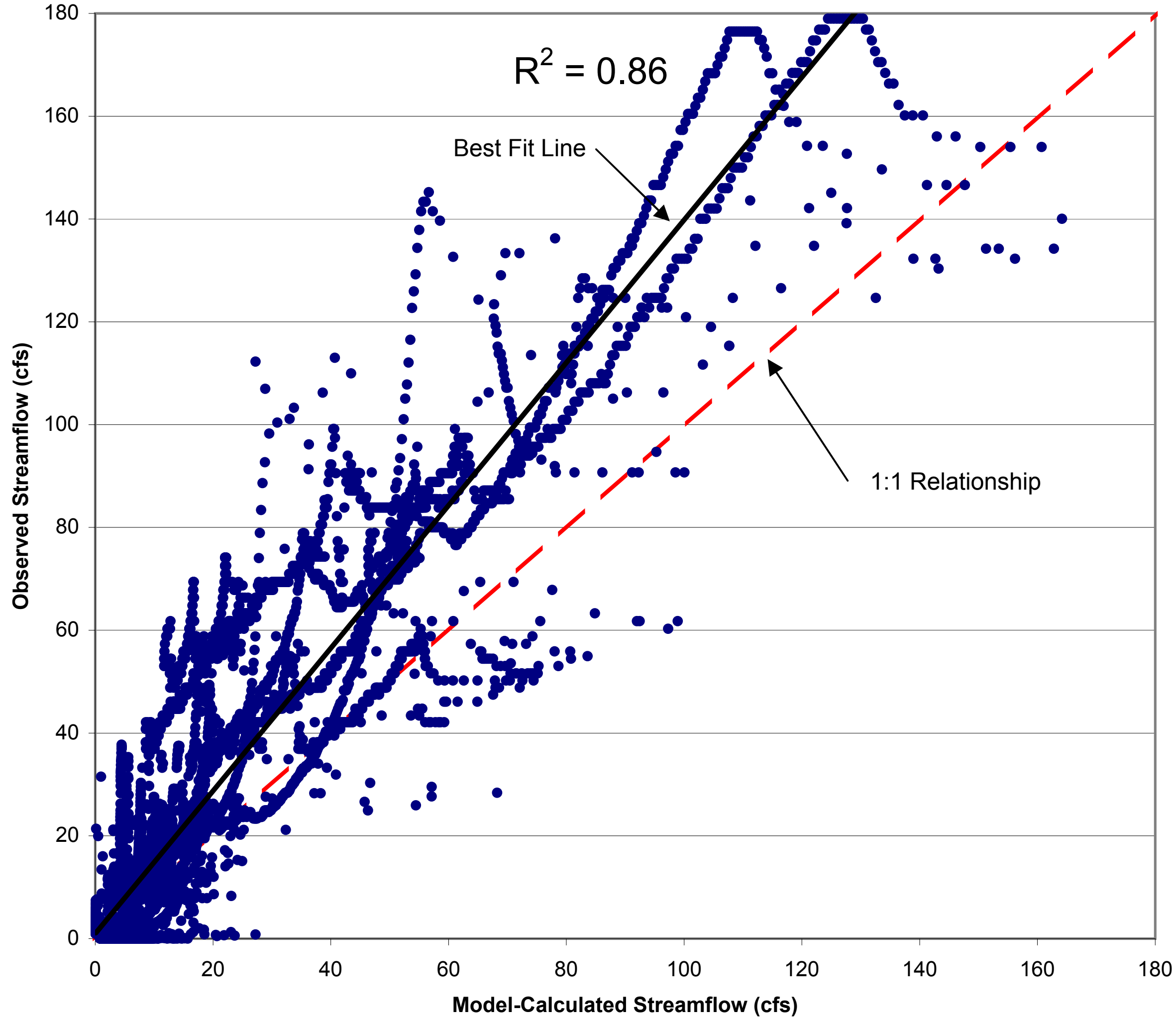
There was significantly less precipitation during the validation period compared to the calibration period. Monitoring location T-1, which includes a large percent imperviousness both overpredicted and underpredicted peak flows (Figure 5-2). Since the model did not include the aquifer component for this area, during extended periods without rainfall the model did not produce streamflow. Streamflows recorded identified a small baseflow consisting of approximately 2 cfs.

Monitoring location T-2 is the most downstream monitoring station. Here the model is less accurately predicting streamflow due to insufficient baseflow. At its longest drought period, the model predicts a baseflow of less than 10 cfs while measured streamflow was approximately 35 to 50 cfs (Figure 5-6). After periods of rain, the model converges to the observed streamflow values but then diverges as no more precipitation is available. These results are consistent with monitoring locations T-7 and T-9 as well.

The model predicts large peaks followed by long recession curves at location T-8. The observed streamflows have much smaller peaks or no peaks with very little baseflow. The total streamflows at this location are fairly small and do not contribute a large percentage of the overall flows to the watershed.

Hourly observed streamflows were plotted with the model computed streamflows in Figure 5-7. The correlation coefficient is 0.93 and the coefficient of determination is 0.86. The model is more accurately predicting these streamflows compared to the calibration dataset. This is most likely because the extreme

Figure 5-7: Calculated vs. Observed Streamflow - Validation



precipitation events observed in October 2005. The model seems to be consistently under-predicting streamflows (Figure 5-7). However, the datapoints to fall along the 1:1 best fit relationship.

CHAPTER 6

DISCUSSION

Summary

The majority of the Pennichuck Brook watershed has soils with very high infiltration rates. These infiltration rates are often significantly higher than precipitation rates which causes little to no direct runoff. The majority of the infiltrated water enters the streams within about 5 days following the storm event. A simple runoff model cannot accurately portray this watershed. The aquifer and baseflow component of SWMM is absolutely essential in modeling this watershed. A simple recharge model combined with an analytical groundwater model would be able to yield similar runoff results, but would lack the water quality component provided in SWMM.

The water level transducers with attached dataloggers are essential in collecting continuous streamflow data. Some problems were encountered when using the dataloggers in the streams. At two adjacent sites, the cord connecting the datalogger to the transducer was severed. The majority of the cords had been installed into the streambed or encased in pvc piping. It was suspected that an animal had chewed each of these cords. Additionally dead batteries and malfunctioning dataloggers caused several gaps in streamflow data.

The model assumes the entire watershed aquifers to be homogeneous throughout. This made the calibration phase of modeling more manageable. Actual conditions throughout the watershed may warrant a heterogeneous aquifer model. This could help the model to more accurately predict streamflows. To calibrate this type of model, streamflows would need to be measured for each subwatershed. This would involve a significantly greater amount of work than was required in the Pennichuck Model. Another watershed characteristic which contains heterogeneities that are ignored in the model is wetland storage. The size, makeup, and storage capacity of wetlands throughout the model vary significantly. These wetlands may provide additional detention time for both surface runoff and groundwater baseflow. If time allowed, these wetlands could be incorporated into the model both by adjusting depression storage values and by adding storage nodes between the subcatchments and their respective downgradient stream channel.

Another limitation of the model is weather variation. One weather/precipitation file was created for the entire watershed. There are no NCDC weather stations located within the watershed that contain a significant continuous period of data. There are however several home weather stations that record continuous weather information that are located in or very near the watershed. Upon reviewing several of these weather stations much variation is visible within the watershed. This is especially prominent during heavy thunderstorms where a part of the watershed may not see any precipitation.

Conclusions

The model predicts reasonably accurately the same trends in runoff and streamflow within the watershed. As stated in the scope of work, the model will ultimately be used to assess the water quality within the watershed. Therefore, the model error is not significant and is not expected to cause an unreasonable amount of error in the water quality determination. The calibration and validation results verify that the model has been calibrated and can predict reasonably accurately an independent set of data. This was necessary due to the fluctuations in precipitation.

The model consistently indicates that there is little to no direct runoff from pervious areas in the watershed. This was as expected due to the rapid infiltration rates encountered throughout the watershed. These findings demonstrate the importance of the correct handling of stormwater runoff from developed areas. New impervious or paved areas cause almost complete runoff of precipitation if uncontrolled and conveyed directly to adjacent streams or water bodies. This results is a very large increase in runoff which must be detained and infiltrated via detentions basin or on-site infiltration devices. Runoff from impervious areas should be directed toward buffer areas where it can infiltrate. Unfortunately, simply infiltrating urban stormwater near Pennichuck Brook will not provide complete treatment for water quality. This is because of the high percolation rates causing very little detention time that is necessary for the soils to naturally treat the stormwater. Maintaining a healthy vegetative cover with a thick organic layer will help to increase treatment received by stormwater as it infiltrates.

Additional Work

This project has provided a calibrated model to predict runoff and baseflow for the watershed. In order to fully assess the condition of the watershed, the water quality component (Part 2) would need to be completed. Pennichuck Water Works and NRPC have collected water quality data in both the reservoirs and streams throughout the watershed over the last decade. This data, along with additional data currently being collected, could be used to calibrate the model for total suspended solids and total phosphorus. The model setup would require pollutant buildup and washoff functions as well as a basic in-pond model for each pollutant. The pond/reservoir modeled phosphorus concentrations could then be compared to the Vollenweider curve to ensure that the water quality is below the eutrophic curve.

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